Dynamics of a laser-assisted Z-pinch EUV source

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Diagnostic techniques:

- absolutely calibrated time integrated EUV spectroscopy
- 2 µm spatially resolved time integrated in-band EUV imaging
- in-band EUV filtered absolutely calibrated photodiode
- EUV filtered fast photodiode
- time- and spatially-resolved fast gated visible emission spectroscopy
- time of flight of ions with Faraday cup
- Rogowski coil characterisation of discharge current
- Angular thin film deposition debris study
Laser Assisted Vacuum Arc (LAVA) lamp

Two rotating disc electrodes with a thin liquid metal coating,

Anode wheel (GND)

Cathode wheel (live)

Liquid metal baths

In vacuum (~10^{-5} mbar)
Laser Assisted Vacuum Arc (LAVA) lamp

Two rotating disc electrodes with a thin liquid metal coating, ablate the cathode.
Laser Assisted Vacuum Arc (LAVA) lamp

Two rotating disc electrodes with a thin liquid metal coating,

- ablating the cathode,
- laser plasma triggers discharge and leads to Z-pinch.

➢ Work just published:

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Two rotating disc electrodes with a thin liquid metal coating, ablate the cathode which is live (right hand side), discharge lead to Z-pinch.

Work just published:
Laser Assisted Vacuum Arc (LAVA) lamp

- **Visible spectroscopy:**

  - 4 mm inter electrode gap imaged onto 3 mm slit of Czerny-Turner spectrometer via 3 silvered mirrors and a Dove prism
  - Spectral range of ~ 380 nm – 610 nm
Laser Assisted Vacuum Arc (LAVA) lamp

- Spatial resolution of \( \sim 300 \, \mu m \) (4 mm imaged to 4.8 mm at ICCD with 26 \( \mu m^2 \) pixel size)
- Temporal resolution \( \sim 8 \, \text{ns} \) (minimum ICCD gate time \( \Delta t \))
- Spectral resolution \( \sim 1 \, \text{nm} \) (instrumental broadening)

- Spectra recorded for \( t_{\text{delay}} = 0 \rightarrow 1.4 \, \mu s, \quad V_{\text{discharge}} = 3 \, kV \rightarrow 6 \, kV \), with pure Sn and galinstan

\[ \text{Sn: } E_{\text{discharge}} = 4 \, J \, (4.5 \, kV), \quad E_{\text{laser}} = 12 \, mJ, \quad t_{\text{delay}} = 400 \, ns, \quad \Delta t = 100 \, ns \]
Time delay between laser pulse & onset of discharge varied for material:

- galinstan: ~ 300 ns $\tau \sim 620$ ns
- pure tin: ~ 200 ns $\tau \sim 600$ ns

Galinstan 4.5 kV:
Laser Assisted Vacuum Arc (LAVA) lamp

Galinstan: $E_{\text{discharge}} = 4 \text{ J (4.5 kV)}, E_{\text{laser}} = 12 \text{ mJ}, \Delta t = 1 \mu\text{s}$

Counts

Sn III

In III

In III

Many lines left to be diagnosed (In & Ga?)

Spectra saturated, $\text{counts}_{\max} \sim 15000$

EUV emitting region (6 nm – 18 nm) time integrated imaging:

Shot (a)  Shot (b)  Shot (c)  Shot (d)

Field of view

1.3 mm

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- No discharge, 12 mJ laser pulse on Sn:
  - $t_0$ onset of laser pulse, 10 ns gate width

![Graph showing laser pulse effects on Sn](image)

- 100 ns after laser pulse, 50 ns gate width

![Graph showing laser pulse effects on Sn](image)

- Cathode Wheel
- Laser
- Anode wheel
- LPP

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Counts_{max} = 20000
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100 ns delay with 100 ns gate time

Counts_{\text{max}} = 10000
Laser Assisted Vacuum Arc (LAVA) lamp

200 ns delay with 100 ns gate time

Counts_{max} = 15000

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300 ns delay with 100 ns gate time

Counts_{\text{max}} = 20000

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400 ns delay with 100 ns gate time

Counts_{max} = 8000

Wavelength (nm)

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500 ns delay with 100 ns gate time

Counts_{\text{max}} = 3000

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600 ns delay with 100 ns gate time

Counts_{max} = 4000

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700 ns delay with 100 ns gate time

Counts_{max} = 4000

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800 ns delay with 100 ns gate time

Counts\textsubscript{max} = 2000
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900 ns delay with 100 ns gate time

Counts_{max} = 4000

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Sn ion time of flight:

- d = 45 cm
- $\phi_{\text{aperture}} = 2.7$ mm
- $B \sim 65$ mT
- $V_{\text{bias}} = -25$ V
- $R_{\text{load}} = 296 \Omega / 996 \Omega$

Discharge:

<table>
<thead>
<tr>
<th>Discharge</th>
<th>Peak ion velocity:</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 V</td>
<td>0.25 keV</td>
</tr>
<tr>
<td>2.45 J (3.5 kV)</td>
<td>1.84 keV</td>
</tr>
<tr>
<td>4 J (4.5 kV)</td>
<td>2.03 keV</td>
</tr>
<tr>
<td>6 J (5.5 kV)</td>
<td>3.48 keV</td>
</tr>
</tbody>
</table>

Averages of 32 signals for ion currents ($E_{\text{laser}} = 12$ mJ)

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Stark broadening analysis:

To assume LTE checked McWhirter criterion:

\[ Ne \geq 1.6 \times 10^{12} (T)^{\frac{1}{2}} (\Delta E)^{3} \]

\[ \therefore Ne \geq 1.9 \times 10^{15}\text{cm}^{-3} \]
Laser Assisted Vacuum Arc (LAVA) lamp

- Boltzmann electron temperature estimates

  - Range of electron temperatures estimated for Sn III and Sn IV lines (~ 2 eV – 6 eV)
    -> Saha estimate of the **ion temperature in agreement** for this range

- Not confident in the Boltzmann data, further work needed. Statistical weight issue?

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Conclusions

- We have recorded **time- and spatially-resolved** visible emission spectra for **Sn** and **galinstan** for discharge voltages of **3 kV – 6 kV** (along with 0 V)

  - **Clear broadening** during the onset of discharge and during pinch phase
    - Densities of up to ~ $5.5 \times 10^{18}$ cm$^{-3}$ following pinch phase

  - A range of temperatures have been estimated (~ 2 eV – 6 eV)
    - Further work needed to increase confidence

  - Finer time steps ($\Delta t = 20$ns) **to be analysed** to further show evolution of plasma

  - Further **diagnosis of Ga and In lines** needed (any advice/help welcome)
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LAVA-lamp, Speclab, UCD
1 μs gate time:

Sn, 4 J (4.5 kV), trigger laser 12 mJ, color scale (min – max): 0 - 15000 counts

Sn, 4 J (4.5 kV), trigger laser 12 mJ, color scale (min – max): 0 - 5000 counts

Saturated
1 μs gate time:

Sn, 4 J (4.5 kV), trigger laser 12 mJ
Galinstan: $E_{\text{discharge}} = 4 \text{ J (4.5 kV)}, E_{\text{laser}} = 12 \text{ mJ}, \Delta t = 1 \mu\text{s}$

Many lines left to be diagnosed (In & Ga?)

Sn: $E_{\text{discharge}} = 4 \text{ J (4.5 kV)}, E_{\text{laser}} = 12 \text{ mJ}, \Delta t = 1 \mu\text{s}$

Spectra saturated, counts$_{\text{max}} \sim 15000$
Translational Langmuir probe

One bath removed

Faraday = 0.057 cm²

$A_{\text{Faraday}} = 0.057 \text{ cm}^2$

$d_{\text{Faraday}} = 50 \text{ cm}$

$A_{\text{Langmuir}} = 0.103 \text{ cm}^2$

$d_{\text{Langmuir}} = 8.6 \text{ cm}$

$V_{\text{bias}} = -25 \text{ V}$

$R_{\text{load}} = 100 \Omega$

Liquid metal bath

Electrode wheel

Heater current feed-through

Electrode rotation shaft